CAAP Quarterly Report

Date of Report: *October 10, 2017*

Contract Number: *DTPH5614HCAP04*

Prepared for: *Arthur Buff, Project Manager, PHMSA/DOT*

Project Title: *Embedded Passive RF Tags towards Intrinsically Locatable Buried Plastic Material*

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For quarterly period ending: *October 10, 2017*

Business and Activity Section

(a) Generated Commitments

Project abstract: Accurate and reliable locating, identifying and characterizing the buried plastic pipes from the ground surface in reducing the likelihood of hit them is critical and imperative to reduce the pipeline incidents. In this collaborative research, a new harmonic radar (frequency doubling) mechanism for smart RF tags design that can detect plastic pipes deeply buried in various soils conditions will be investigated, achieved through efficient tags and highly sensitive readers design, and coupled with intelligent signal processing. The proposed low-cost, small thin-film form passive RF tags can directly be embedded in plastic pipes. It will be able to withstand high temperature processing of plastics and stress involved with horizontal tunneling/drilling of buried pipes. The embedded RF tags have the capability to not only precisely locate the buried plastic pipes, but also have integrated sensing functionality, which can measure the strain-stress changes in the plastic materials. Finally, the vast amount of acquired sensing data from individual tags will be integrated to the advanced signal processing for better data categorization and mining. An innovative prognostics framework for better asset life-cycle management will be developed.

A complete solution is needed that helps in identifying individual buried pipes, their precise location, determining their integrity and sensing for leaks. Buried pipes are expected to have a lifetime of greater than 30 years that are designed to carry a range of liquid and gaseous materials. Among the many pipe technologies, demand for plastic pipes is growing largely because of their low-cost and potential for long life time. Any tags or sensors that are incorporated within these pipes should be able to withstand harsh conditions with a lifetime meeting or exceeding that of the pipes, and should be battery free (passive tag). Furthermore, the overall system should be compact, low-cost, and easy to operate. With advanced techniques to bury the pipes using tunneling approaches it is necessary that tags withstand the associated stress and handling during construction work. Typically, the pipes are buried 3 feet or deeper in the ground and thus the reader should be able to interrogate the tags at these and at higher depths (greater than 5ft is desired).

As summarized in Introduction section, significant advances have been made in the area of electronic tagging of buried objects. However, most of these tags are an afterthought as they are not integral part of the infrastructure. These tags are typically large and are buried along with the objects.

This is simple if open trenching is carried out. However, for plastic pipes that are buried using tunneling this approach will not suffice without making the tags an integral part of the plastic pipe. Furthermore, no RF tags are commercially available that will allow in sensing of the environment and the integrity of the buried object during its life time. Smart RF tag designs are necessary as power harvesting and storage techniques will also have limited life time as the rechargeable batteries (or capacitors) and the associated circuit (e.g., piezo power harvester) will have a limited lifetime. Meanwhile, no advanced data processing algorithms are available for optimally manage and use the vast amount of information embedded into the received RF signals from the proposed new tags. Under this three-year project, the specific technical objectives/goals of the proposed research are:

1) Design and development of new passive harmonic radar based smart RF tags with long range detection guided by industry partners;
2) Design robust and miniature tags such that they can directly be embedded in plastic pipes during manufacturing;
3) Investigate on-tag strain-stress sensing capabilities and efficient data transmission;
4) Investigate new massive RFID data mining, processing and classification algorithms with experimental testing;
5) Develop a Bayesian Learning based pipeline hazardous prognostics methodology using discrete sensing data;
6) Intrinsically locatable pipe materials demonstration and field testing using representative pipe specimens with GPGPU acceleration.

Another equally important objective of this proposed research is to engage MS and PhD students who may later seek careers in this field by exposing them to subject matter common to pipeline safety challenges. Since the project being kicked off, three PhD students from both universities and several MS students have been recruited and trained through this CAAP program and apply their engineering disciplines to pipeline safety and integrity research. The PIs think the educational component is a very important part of the CAAP project and will integrate with research activities with various educational activities to prepare the next generation engineers for gas and pipeline industry. The educational and research impacts sponsored by CAAP has been recognized within the university (see *support letter 3 from Associate Vice Chancellor of university*) and nationally (Two current CAAP-funded students at CU haven been recognized at ASNT annual research symposiums in 2014 and 2015). Specific educational objectives and goals are:

1) Guide and train graduate students at University of Colorado-Denver and Michigan State University for the pipe integrity assessment and risk mitigation;
2) Integrate with existing mechanisms for undergraduate research at University of Colorado-Denver and Michigan State University for early exposure of pipe industry research to potential engineers;
3) Improve the current curriculum teaching at University of Colorado-Denver (ELEC5644 Nondestructive Evaluation and ELEC3817 Engineering Probability and Statistics) and Michigan State University (ECE802-1 Microwave and Millimeter Wave Circuits and ECE802-2 Electronic Systems Packaging) using the achievement from the proposed research;
4) Invite pipe industry expert (see support letters later in this proposal) to deliver seminar/workshops to undergraduate/graduate students about the challenges and opportunities in gas and pipeline industry;
5) Encourage the involved students to apply internships at DOT and industry to gain practical experiences for the potential technology transfer of the developed methodologies.

The above-mentioned goals and objectives of the proposed Competitive Academic Agreement Program (CAAP) project will be well addressed and supported by the proposed research tasks. Development, demonstrations and potential standardization to ensure the integrity of pipeline facilities will be carried out with the collaborative effort among different universities and our industry partners. The quality of the research results will be overseen by the PIs and program manager and submitted to high-profile and peer-reviewed journals and leading conferences. The proposed collaborative work provides an excellent environment for integration of research and education as well as tremendous opportunities for two universities supported by this DOT CAAP funding mechanism. The graduate students supported by this CAAP research will be heavily exposed to reliability and engineering design topics for emerging pipeline R&D technologies. The PIs have been actively encouraging students to participate in past and ongoing DOT projects and presented papers at national and international conferences. Students who are not directly participating in the CAAP project will also benefit from the research findings through the undergraduate and graduate courses taught by the PIs and attending university-wide research symposium and workshop, e.g. RaCAS at CU-Denver. The proposed research involves pipeline industry to validate and demonstrate scientific results and quantify engineering principles by working closely with industry partners. They will also collaborate with the CAAP team on this research which may include but is not limited to information exchange, mutual meetings, providing CU and MSU with appropriate technical support for the target application.

(b) Status Update of Past Quarter Activities

Task 1 – On-tag Sensing and Signal Processing

A: Soil Dielectric Permittivity Approximation

Dielectric permittivity is required in order to calculate the depth of the buried tag in the soil medium. A method to approximate the permittivity is shown in this section. The dielectric permittivity of any medium directly affects the phase velocity of the propagating signal.

$$\boldsymbol{v_p = \frac{c}{\sqrt{\epsilon_r}}} \qquad (1)$$

Where, v_p is the phase velocity, c is the speed of light, ϵ_r is the dielectric permittivity of the medium.

The wavelength of the given medium is also a function of phase velocity.

$$\boldsymbol{\lambda = \frac{v_p}{f}} \qquad (2)$$

Where, λ is the phase wavelength, f is the frequency of the signal.

The phase of the signal repeats after every 360 degree or single wavelength completion, which means that the change in phase is directly proportional to the change in wavelength as shown below.

$$\boldsymbol{\frac{\Delta\phi}{360^\circ} = \frac{\Delta\lambda}{\lambda}} \qquad (3)$$

Where, $\Delta\phi$ is the phase change in degrees according to the wavelength $\Delta\lambda$.

Wavelength of any medium is directly proportional to the wavelength in air, according to the equation below.

$$\boldsymbol{\lambda_M = \frac{\lambda_A}{\sqrt{\epsilon_r}}} \tag{4}$$

Where, λ_M is the wavelength in medium, λ_A is the wavelength in air.

By substituting the medium wavelength from Eq.4 to Eq.3 and rearranging the equation.

$$\sqrt{\epsilon_r} = \boldsymbol{\frac{\Delta\phi}{360°}\frac{\lambda_A}{\Delta\lambda}} \tag{5}$$

In Eq.5, λ_A is known due to frequency, $\Delta\lambda$ can be moved, and $\Delta\phi$ can be measured.

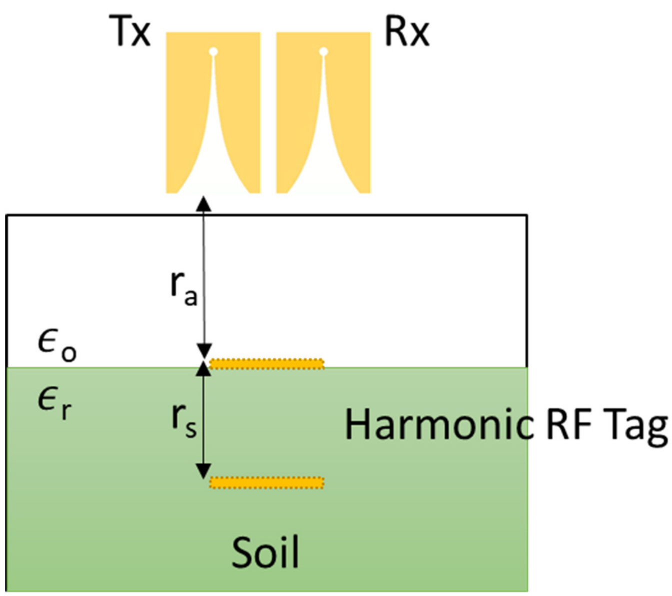

Fig. 1 Setup for approximating permittivity of the soil

The developed experimental setup for RF tag communication can be used to measure the phase of the received signal. RF transmitter sends the signal at frequency $f_o$towards harmonic tag and the tag reflects back the phase information at $2f_o$. Due to the inclusion of harmonic component, the Eq.5 needs to be changed accordingly. The phases of forward propagating signal (f_o) and back propagating signal ($2f_o$) are added at the receiver for the net change in phase. The change in phase can be calculated as follows:

$$\boldsymbol{\Delta\phi^{FH} = \Delta\phi^F + \Delta\phi^H} \tag{6}$$

$$\Delta\phi^{FH} = \left(\frac{\Delta\lambda^F}{\lambda^F} + \frac{\Delta\lambda^H}{\lambda^H}\right)360°$$

$$\Delta\phi^{FH} = 3\left(\frac{\Delta\lambda^F}{\lambda^F}\right)360°$$

$$\frac{3}{\lambda^F} = \frac{\Delta\phi^{FH}}{\Delta\lambda^F}\frac{1}{360}$$

Substitute $\frac{3}{\lambda^F}$ with $\frac{\sqrt{\epsilon_r}}{\lambda_A^{FH}}$, where $\lambda^{FH} = \frac{\lambda^F}{3} = \frac{\lambda_A^{FH}}{\sqrt{\epsilon_r}}$ and $\Delta\lambda^F$ is replaced with r_s.

$$\boldsymbol{\epsilon_r = \left(\frac{\Delta\phi^{FH}}{r_s}\frac{\lambda_A^{FH}}{360}\right)^2} \tag{7}$$

B: Harmonic TAG Distance Estimation

The harmonic RF system consists of two operating bands (fundamental and harmonic), which makes this setup more accurate, clutter free and robust over conventional passive RF system. The transmitted and received signal from interrogator can also be used for estimating the distance between the source and the RF tag. The phase of the received signal can be translated into distance using wavelength of the given medium. The uncertainty in estimation arises when the separation between source and tag is greater than a single wavelength, due to the phase repetition after completion of each wavelength. To eliminate this uncertainty several different frequencies can be used for communicating with tag. The interrogator will receive a different phase for each frequency and the combination of all those phases will be unique within a certain range of separation. The maximum range for a given set of frequencies can be calculated by taking least common factor of their respective wavelengths. After that maximum distance, the combination of phases will start repeating again. More number of frequencies can be introduced for increasing the range of the distance estimation system.
The forward propagating signal (f_o) and the backward propagating signals ($2f_o$), both will have a net phase shift of ϕ^F and ϕ^H respectively, shown on Fig.2. The interrogator receives a phase that is the summation of the fundamental (ϕ^F) and the harmonic (ϕ^H) phase.

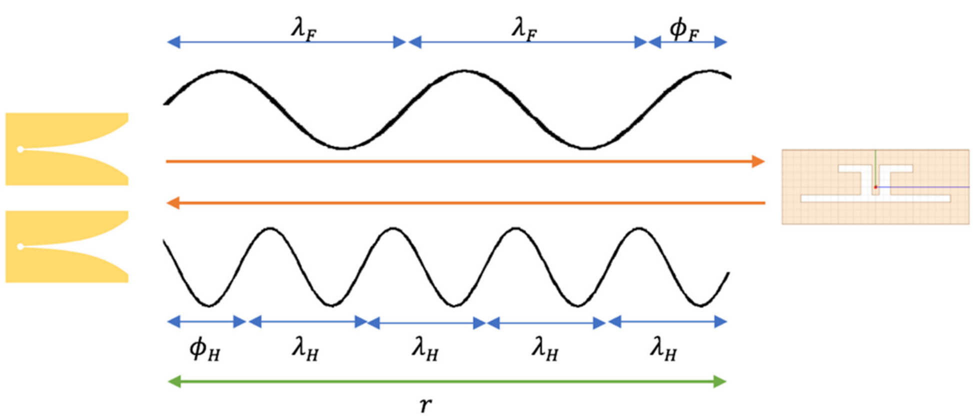

Fig. 2 Distance estimation using phase information in harmonic RFID system

The separation *r* between the source and the tag can be presented as Eq. 8 and 9 for both bands of frequencies where *n* and *m* are the number of completed fundamental (λ^F) and harmonic (λ^H) wavelengths, respectively. The wavelength is assumed to be a known parameter for all equations shown below.

$$\boldsymbol{r = n\lambda^F + \phi^F + \delta^F} \tag{8}$$

$$\boldsymbol{r = m\lambda^H + \phi^H + \delta^H} \tag{9}$$

The distance travelled by the signal from transmitter-to-tag-to-receiver is double of the given separation r, shown in Eq. 10.

$$2r = n\lambda^F + m\lambda^H + \phi^F + \phi^H + \delta^F \quad (10)$$

To estimate the unknown separation r from the given set of parameters, n and m needs to be calculated from Eq. 8 and 9 using the following optimization approach:

$$\min(n_k\lambda_k^F + m_k\lambda_k^H + \phi_k^F + \phi_k^H - n_i\lambda_i^F - m_i\lambda_i^H - \phi_i^F - \phi_i^H + \delta_i)$$

where, $i = 1,2,3, \ldots, k-1$ and k is the total number of operating frequencies.

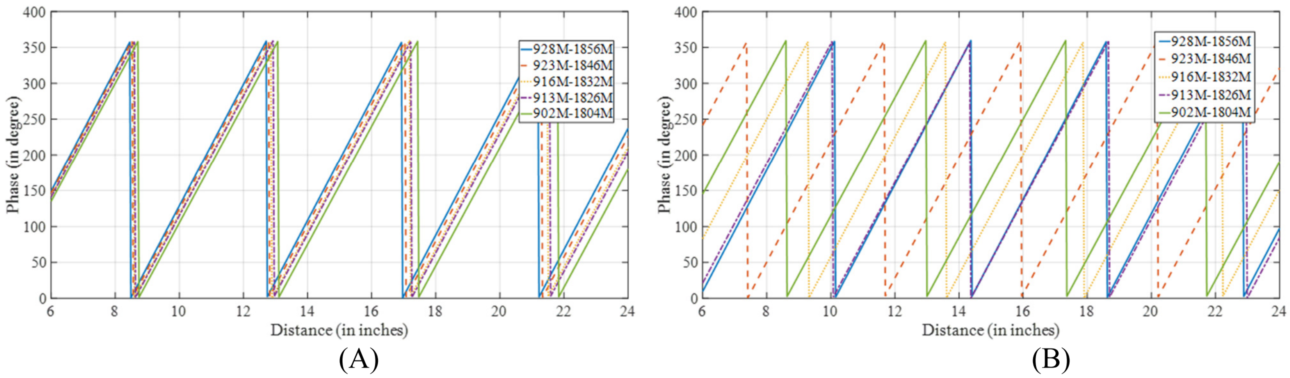

Fig. 3 Pseudo Harmonic Phase Data (A) without offset, (B) With Offset

A pseudo harmonic phase data is generated for testing the modified distance estimation algorithm. Two set of data's are generated: A) with no offset or assuming all the frequency signals are starting at reference phase = 0, B) with offset data creates a similar real world situation where the frequency signal can have any arbitrary reference phase, shown in Fig. 3.

Table 1 shows the results of distance estimation algorithm based on NSGA-II. Starting with a population size of 40 and 100 total number of generation are sufficient for unwrapping phase from pseudo data. Due to the absence of noise and also the known phase offset gives the accurate results with no error.

Actual Distance (inches)	Estimated Distance (without offset)	Estimated Distance (with offset)
8	8.0	8.0
12	12.0	12.0
16	16.0	16.0
20	20.0	20.0
24	24.0	24.0

Table 1. Estimated Distance using new harmonic distance estimation algorithm over with and without offset pseudo data

The phase data is acquired using the developed harmonic RF system operating at 915-1830 MHz bands. All the operating frequencies were selected within the current RFID communication band.

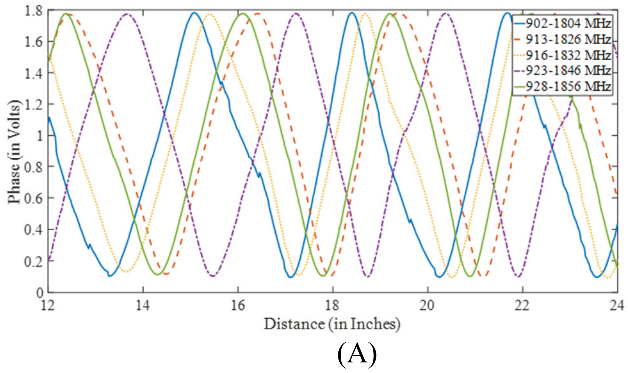

Fig. 4 Experimental Harmonic Phase Data (A) RAW phase data (B) Processed Phase Data

The acquired RAW phase data is the output of the mixer AD8320 shown in Fig. 4(A). The phase data is processed further to eliminate the phase uncertainty due to same voltage level associated with two phases. Phase data is processed according to the slope, if the slope is positive the phase is associated with angles less than 180 and if the slope is negative the phase is associated with angles greater than 180.
The distance estimation algorithm is further applied to the experimental data and the results are shown in Table 2.

Actual Distance (inches)	Estimated Distance	Error Percentage
14	13.2	5
16	15.6	2.5
18	18.7	3.8

Table 2. Estimated Distance using new harmonic distance estimation algorithm over experimental phase data

Task 2 – Design and development of passive harmonic radar based smart RF tags

A: Meandered Dipole Antenna

For low frequency operation, the antenna size gets large. Hence, it is a challenge to reduce the size of the antenna while maintaining a decent amount of gain. A dipole antenna can be designed in meandered fashion to reduce its size. The design and simulation results of the meandered dipole antenna is provided as follows:

A meandered dipole antenna was designed for 400 MHz on Rogers 4350B substrate. The maximum board size is (72mm*80mm), which is smaller compared to a conventional dipole antenna at same frequency. The total realized gain was plotted at 420 MHz. As expected, most of the power is transmitted along the z and y direction. For maximum power transmission, the input impedance of the antenna was matched to 50 Ω. A T-match was used at the feed point for the impedance matching.

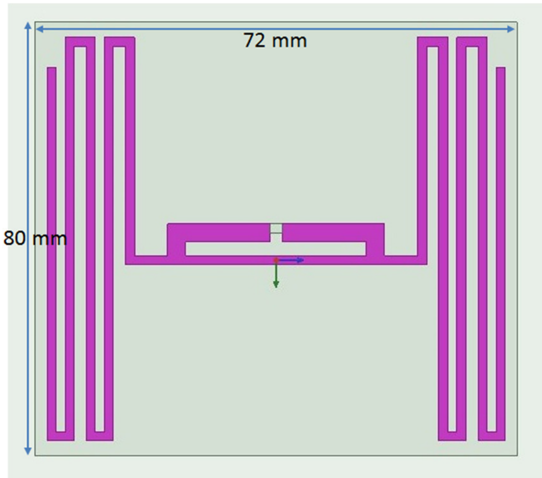

Fig. 5 The 400 MHz meandered dipole antenna on a Rogers 4350B board.

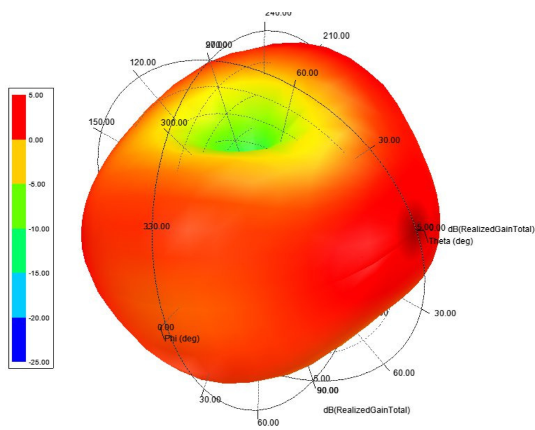

Fig. 6 Realized gain pattern of the 400 MHz antenna with maximum gain along y and z axis.

In similar way the 800 MHz harmonic antenna was designed. Most of the power is radiated along the z and y direction. The size of the harmonic antenna is (40mm*80mm). A T-match and a load line were used to match the input impedance of the antenna to 50 Ω.

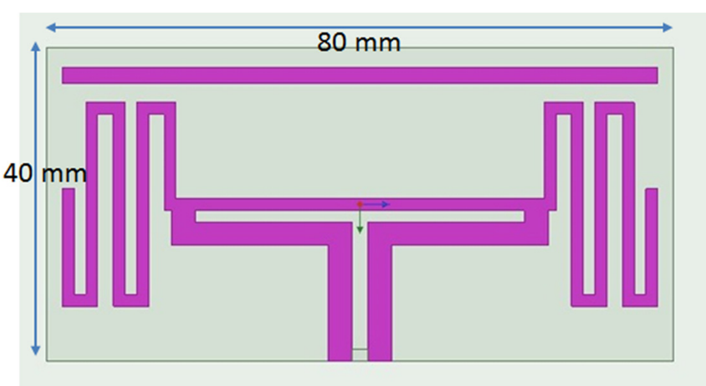

Fig. **7** The 400 MHz meandered dipole antenna on a Rogers 4350B board.

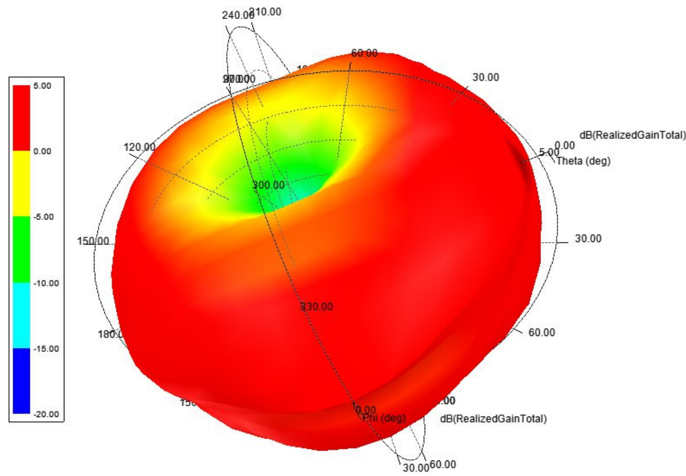

Fig. 8 Realized gain pattern of the 800 MHz antenna with maximum gain along y and z axis.

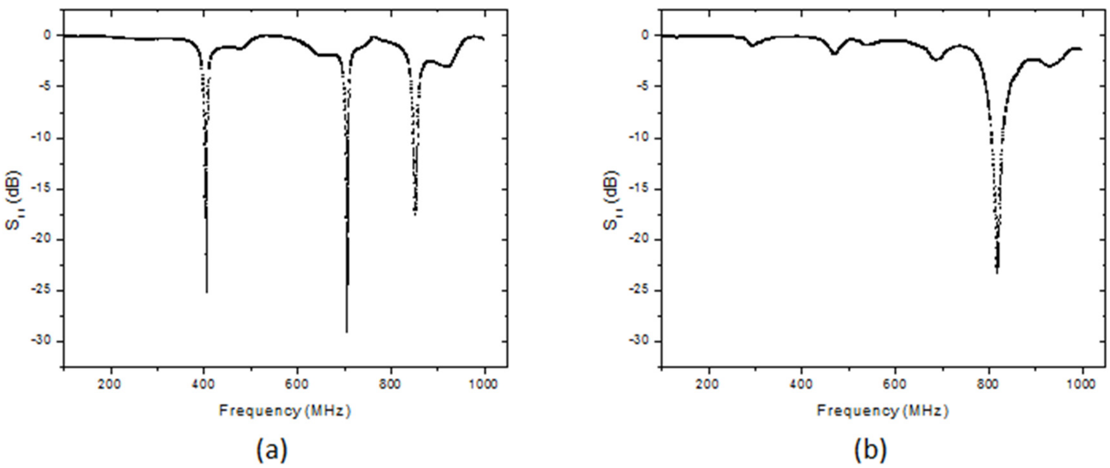

Fig. 9 Measured S11 for (a) 400 MHz antenna and (b) 800 MHz antenna.

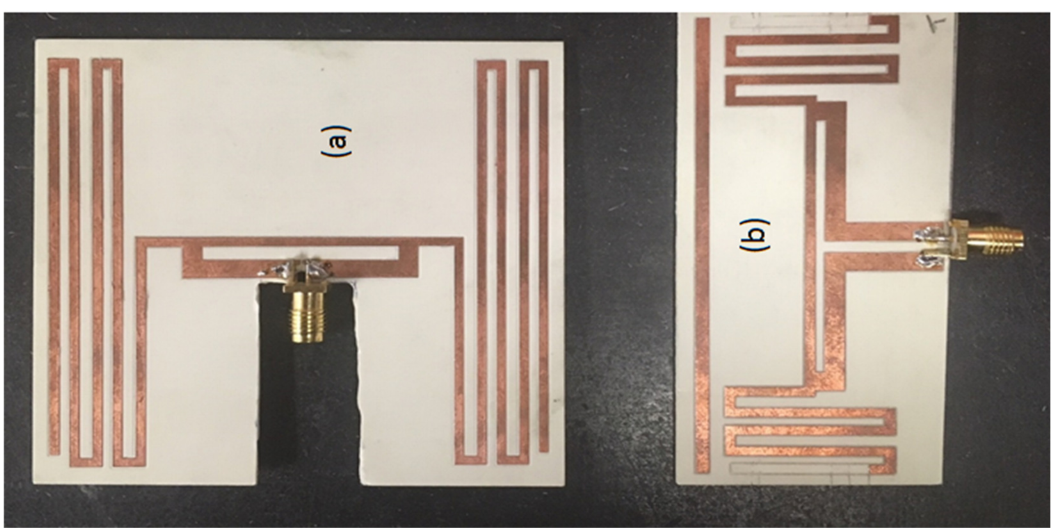

Fig. 10 **T**he fabricated antennas (a) 400 MHz and (b) 800 MHz.

B: Improved Read Range

The schematic diagram of the reader circuit is provided in Fig. 11. A constant frequency of 400 MHz was generated from a stable frequency synthesizer at 406 MHz at -5 dBm. A power amplifier was used to amplify the signal and finally +16 dBm of power was fed to the transmitter antenna after amplification. To reduce the harmonic power level transmitted by the 400 MHz antenna, a low pass filter was used, which provides the harmonic power level 60 dB below the fundamental signal. As the transmitter and receiver antennas are linearly polarized, cross polarization orientation was used for receiving and transmitting antennas to reduce the harmonic power coupling and thus minimizing the noise level. After the reception of harmonic signal from the tag using the 800 MHz receiving antenna, the harmonic signal is passed through a high pass filter to remove the clutter signal created by the fundamental frequency. Once the harmonic signal is filtered out, it is amplified using LNA and finally the signal is captured in a Spectrum Analyzer.

The range of the interrogation depends upon the noise level of the received harmonic power level from the transmitter. Use of sharp roll-off low pass filter and antenna cross-polarization can increase the read range significantly.

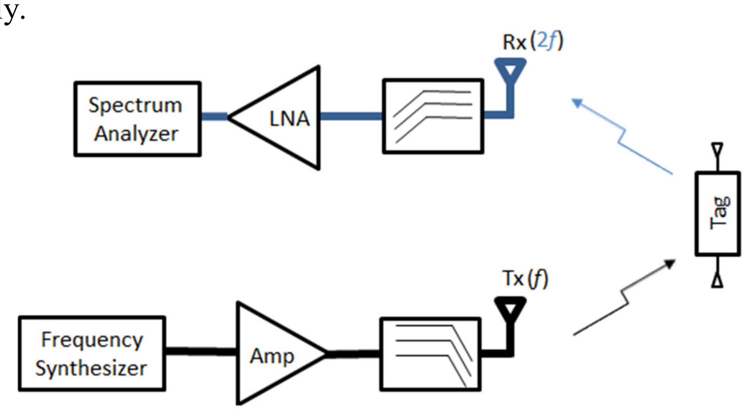

Fig. 11 Schematic diagram of the reader circuit with the harmonic tag.

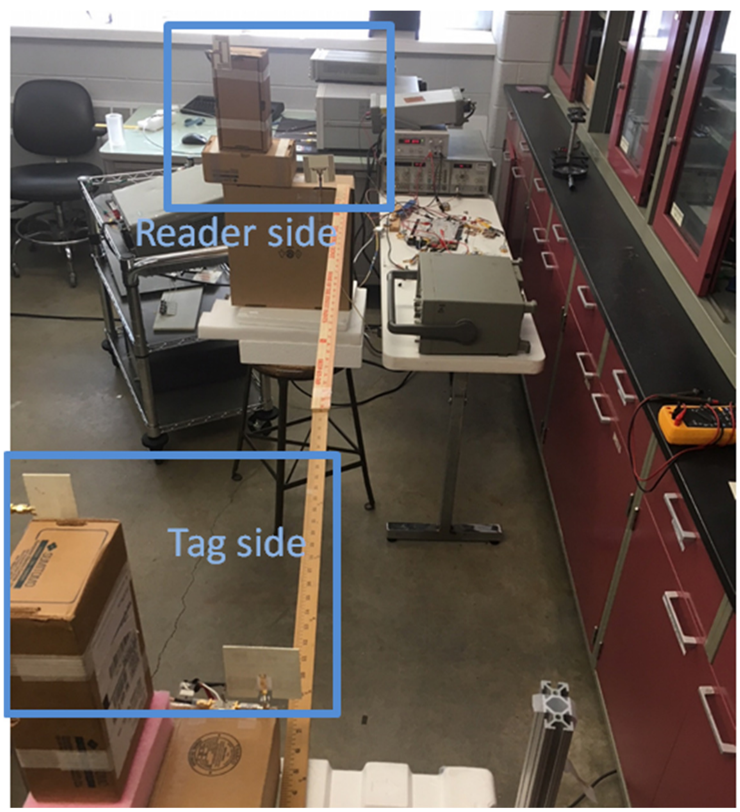

Fig. 12 Measurement setup of the system.

Table 3. Measured received power at different distance

Distance (inches)	Noise Level (dBm)	Received Power (dBm)
62	-31.5	-11.87
70	-32.37	-14.5
80	-29.5	-21.4
100	-32.2	-26.3

(c) Planned Activities for the Next Quarters

Besides the planned activities mentioned in section (b), here is the future work for the next quarter:

ON-TAG SENSING, DATA MINING AND PROCESSING SETUP:

- Implementation of Distance estimation algorithm over lower frequency system
- Sensor Integration
- Multiple Tag Detection and Data Processing

NEW PASSIVE RFID TAG DESIGN:

- Develop meandered antenna compatible within soil medium
- Extend the reader circuit with phase estimation
- Develop wide-band antenna for multi-frequency readings